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MULTIBEAM FORMATION WITH A PARAMETRIC SONAR

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ABSTRACT

Parametric sonar has proven to be an effective concept in sonar applications requiring only a single transmitted beam and relatively low information rates. To be a viable candidate for the broad class of sonar applications that require search sectors greater than the angular extent of the parametrically transmitted beam, techniques must be developed to form multiple transmitted beams or an angularly scanned beam for the parametric source sonar. One technique proposed by Dr. H. O. Berktay in an unpublished report has been evaluated by Applied Research Laboratories of The University of Texas at Austin (ARL/UT) and this report summarizes the results of that work.

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I. INTRODUCTION

A parametric source transmits two relatively high frequency primary signals which mix in the water to generate a signal at a frequency equal to the difference in frequency of the two primary signals. The radiation pattern of the difference frequency has a single lobe and has an angular beamwidth which is generally about the same as the larger beamwidth of the two primary radiation patterns. The parametric sonar has proven to be an effective concept in depth sounding, echo ranging, and acoustic communications applications requiring only single narrow transmitting beams and a relatively low information rate.

In applications that require relatively high information rates over angular sectors greater than the angular beamwidth of the parametric source, techniques must be developed to form multiple contiguously spaced parametric beams or to angularly scan a single parametric beam over the desired angular sector.

During the period 1 December 1972 to 30 September 1973, under ONR sponsorship (Contract N00014-70-A-0166, Task 0008), a laboratory parametric sonar that could produce parametrically generated difference frequency beams that were deflected from the major response axis of the projector was designed and assembled. In a follow-up effort (Contract N00014-70-A-0166, Task 0020) for the period of 1 February 1974 to 31 July 1974) under Defense Advanced Research Projects Agency sponsorship (ARPA), with ONR acting as contract agent, an evaluation of the sonar and of an identification technique of transmitted beams was conducted

This report summarizes the design features of the parametric sonar system, a technique for beam identification, and experimental results obtained with the laboratory parametric sonar.

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II. DESIGN FEATURES OF A PARAMETRIC MULTIBEAM
SONAR TRANSMITTER

Conventional high resolution sonars that have a wide search sector
and a relatively high information rate usually transmit acoustic energy
over the total search sector and form multiple narrow receiving beams
which are contiguously spaced to cover the search sector. All the
multiple receiving beam outputs are repeatedly sampled consecutively
within the pulse length of the system. The angular resolution of the
system and the angular target location are determined by the receiver
beamwidth and the angular location of the receiver beams, and the range
resolution is determined by the pulse length if the beam outputs are
sampled repeatedly at least once during a pulse length period. A varia-
tion of this system operation is to form a single narrow receiving beam
and to electronically scan the beam across the search sector, once during
each pulse length period.

With a parametric source sonar, much of the preceding description
concerning the transmitter and the receiver beam formation must be
reversed. Since narrow transmitted beams are easily formed with the
parametric sonar, it would seem logical, and perhaps even necessary, to
form many contiguously spaced transmitted beams over the search sector
and to utilize a single widebeam receiving pattern. For a parametric
sonar with a very low information rate and a wide angular sector, a
parametric beam could be transmitted at one limit of the angular search
sector and the receiver could be turned on for a time equal to the round
trip travel time for targets at the longest range of interest. The
transmitted beam could then be steered to a contiguous angular location
and the transmission-receiving sequence repeated.

In applications requiring a higher information rate than that just
described, simultaneous transmission of all the beams can occur if each

of the beams has a distinct signal waveform signature such that echoes from various angular locations can be identified in the widebeam receiver. When only a very few beams are required, each beam could possess a different frequency and a simple spectrum analyzer in the receiver could provide angular discrimination of the echoes. As the number of beams is increased, the number of distinct frequencies would increase. Each of the transmission channels would have to have sufficient bandwidth to allow preservation of the desired range resolution, and there would have to be guardbands in the receiver to reduce crosstalk between adjacent channels. Analyses have shown that this is not a very efficient approach to increasing the information rate.

Dr. H. O. Berktay[1] and others at the University of Birmingham in England have analyzed the problem of achieving high information rates in parametric sonars. The method that appeared most promising was to frequency shift key (FSK) each transmitted beam and separate the return echoes with multiple replica correlators in the receiver. Figure 1 illustrates the transmission portion of this technique where four beams are required to cover the entire search sector and where four distinct frequencies are used to make up the four coded pulses.

ARL embarked on a program to design and build a multiple beam parametric sonar under ONR sponsorship during the period 1 December 1972 to 30 September 1973.[2] A multiple stave transducer and a set of tapped electromagnetic delay lines used in a developmental sonar several years ago at ARL served as the basic building blocks for the multibeam parametric sonar transmitter.

Figure 2 is a simplified block diagram of the coded pulse parametric sonar transmitter. The scan generator provides both a clock frequency that determines the transmitted pulsewidth and a time sequenced output that controls the time of transmission of a given pulse to a given sector.
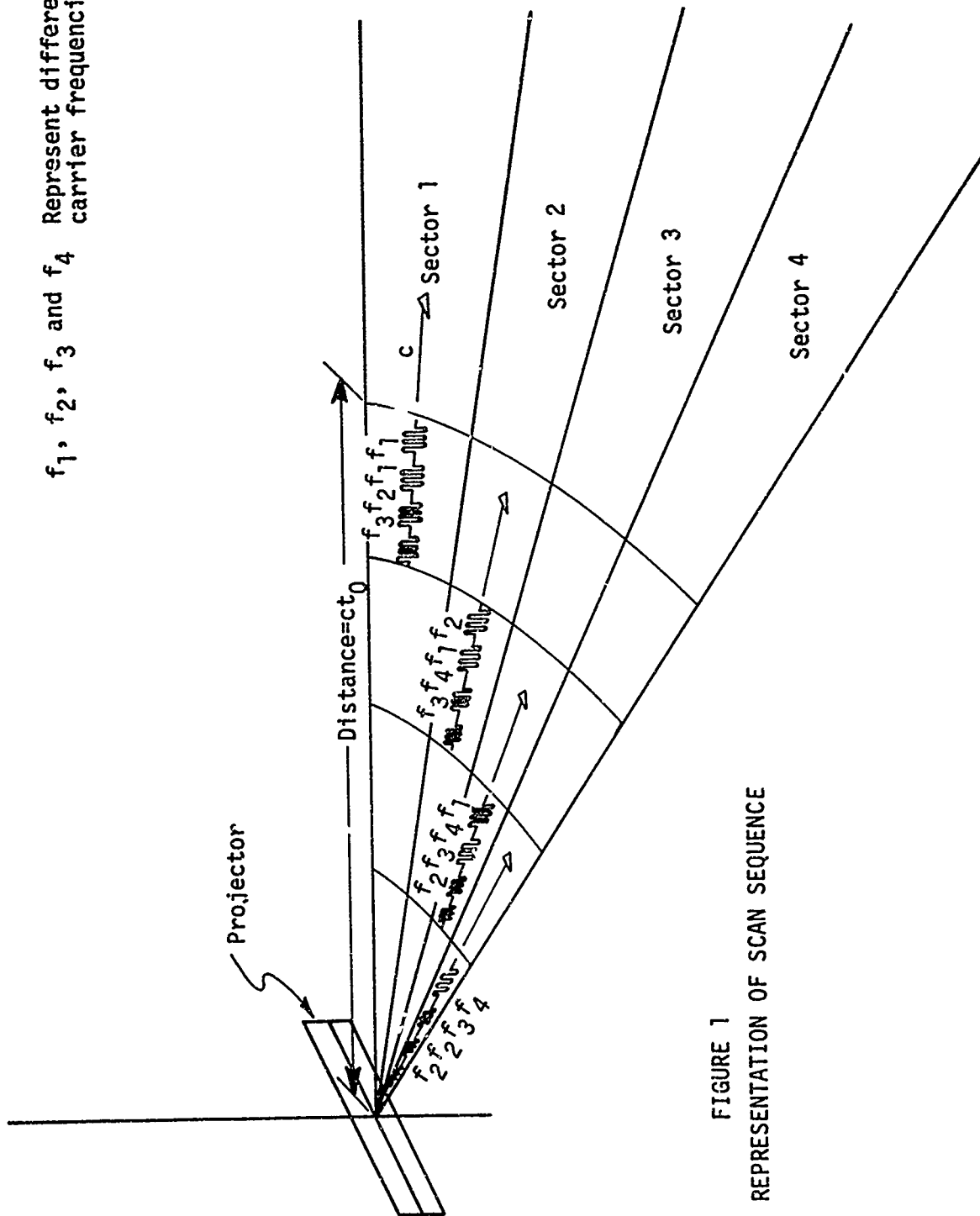
FIGURE 1
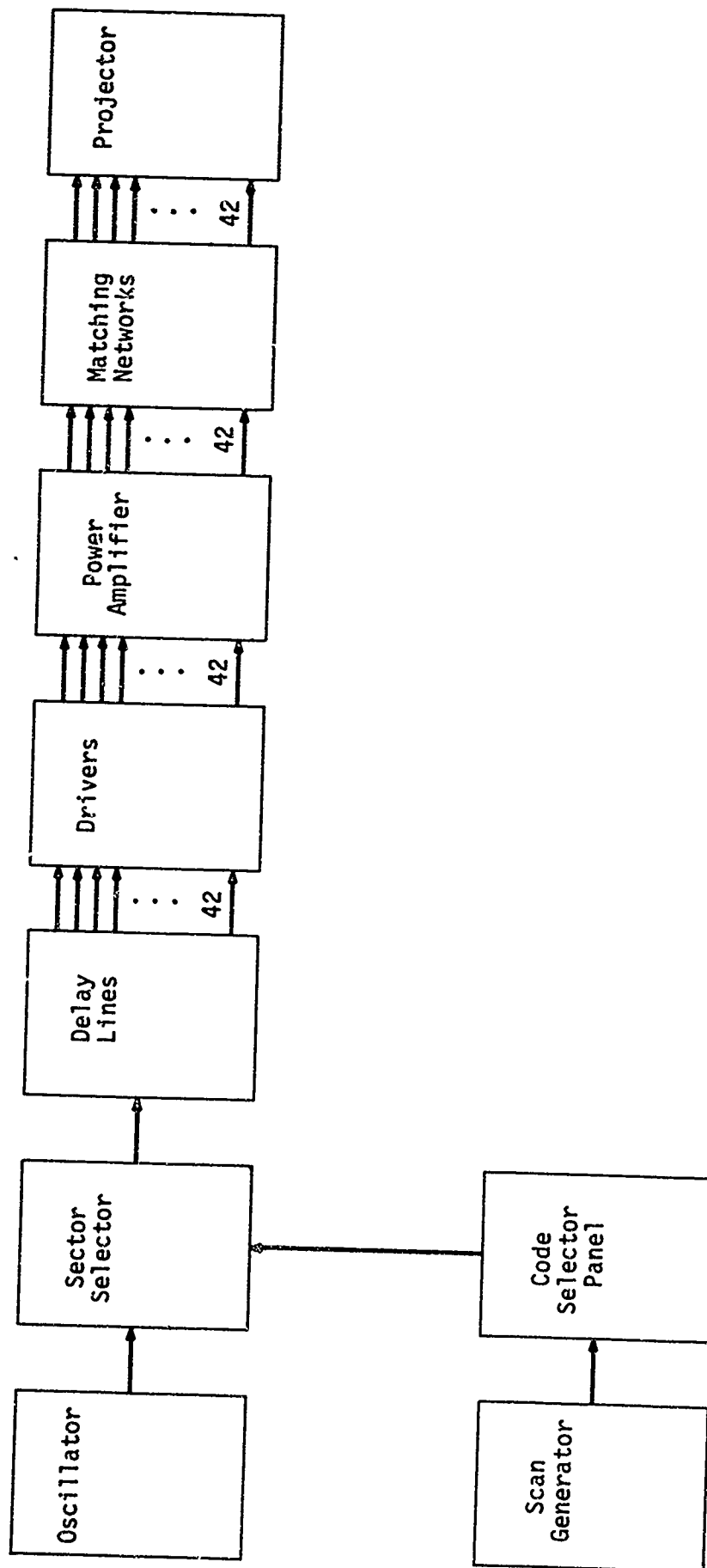
GRAPHIC REPRESENTATION OF SCAN SEQUENCE

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FIGURE 2
BLOCK DIAGRAM OF CODED PULSE TRANSMITTER

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The code selector panel shown in Fig. 2 consists of a patch panel and the necessary logic for assigning frequencies to each pulse sector code generated by the scan generator.

The oscillator is gated by the code selector panel to provide a linear sum of two sinusoidal waveforms. One of these signals is 84 kHz and the other could be 70, 72, 74, or 76 kHz, depending upon the state of the frequency code from the code selector panel.

Sector selector circuits apply the output of the oscillator to one of four delay lines, according to the sector code. The sector selector consists of four gates with common inputs to which the oscillator signal is applied. The output from each of the four gates then drives a separate delay line through a line driver.

Fifteen delay lines in the delay line subsystem vary in total time delay from 12.3 to 184.5 μsec, giving a range of scan angles from 1° to 15° in 1° increments. Each line can be driven by a line driver from either end to steer the beam to either side of the projector axis. Each line has 42 output taps, each connected to the input of the power amplifier driver. The purpose of the power amplifier driver is to provide controllable gain and phase compensation for each channel of the transmitter.

The power amplifier is a set of 42 independent modular power amplifiers mounted in a single chassis. Each amplifier is a class AB_1 amplifier capable of supplying a 10 W cw pulse with a 25% duty cycle to an 8 Ω load.

The matching networks are tuned, air core autotransformers which transform the complex projector impedance to 8 Ω resistive at 76 kHz.

The projector is a 42-stave multielement array 42 in. in length and 4.5 in. in height. Each of the 42 staves has dimensions of

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4.5 x 0.940 x 0.625 in. The staves, an assembly of eight ceramic elements 0.94 x 0.507 x 0.625 in., are stacked on their 0.940 x 0.625 in. faces, with 0.069 in. of chloroprene sandwiched between adjacent elements. The elements in each stave are wired in parallel and each stave is driven separately by one of the power amplifiers.

Tests were conducted at ARL's Lake Travis Test Station (LTTS) to demonstrate the electronic scanning of a parametric beam and to measure its directivity pattern and source level at various steering angles. Standard pulse techniques of measurement were used. The projector of the coded pulse transmitter was mounted on a rotating column in the water; this column allowed rotation on the azimuth and elevation axes. A calibrated spherical hydrophone was placed in the farfield of the projector to measure the transmitted signal as the projector was rotated in azimuth. The range from the projector to the hydrophone was 67 m. The voltage output of the hydrophone was filtered, amplified, gated, peak detected, and recorded on the y-axis of a recorder.

The parametric beams were produced by the simultaneous transmission of two primary beams, with carrier frequencies of 70 and 83.95 kHz. Before measuring the parametric directivity pattern, however, separate directivity patterns were measured by transmitting only one primary frequency at a time. The parametric directivity pattern was then measured by simultaneously turning on both primary beams without changing input power levels. The calculated radiated acoustic power was 52.5 W.

The directivity patterns for deflected beams of ±1°, ±7°, and ±14° are shown in Figs. 3 through 5. Figures 3 and 4 show the respective directivity patterns of 70 and 83.95 kHz for each deflection angle. A comparison of primary beamwidth to difference frequency beamwidth would be meaningful at this point. The measured 3 dB beamwidth of the 70 and 83.95 kHz primary beams was approximately 1° for all scan angles. The measured 3 dB beamwidth of the difference beams shown in Fig. 5 widened as the scan angle increased; this was an expected result. The parametric

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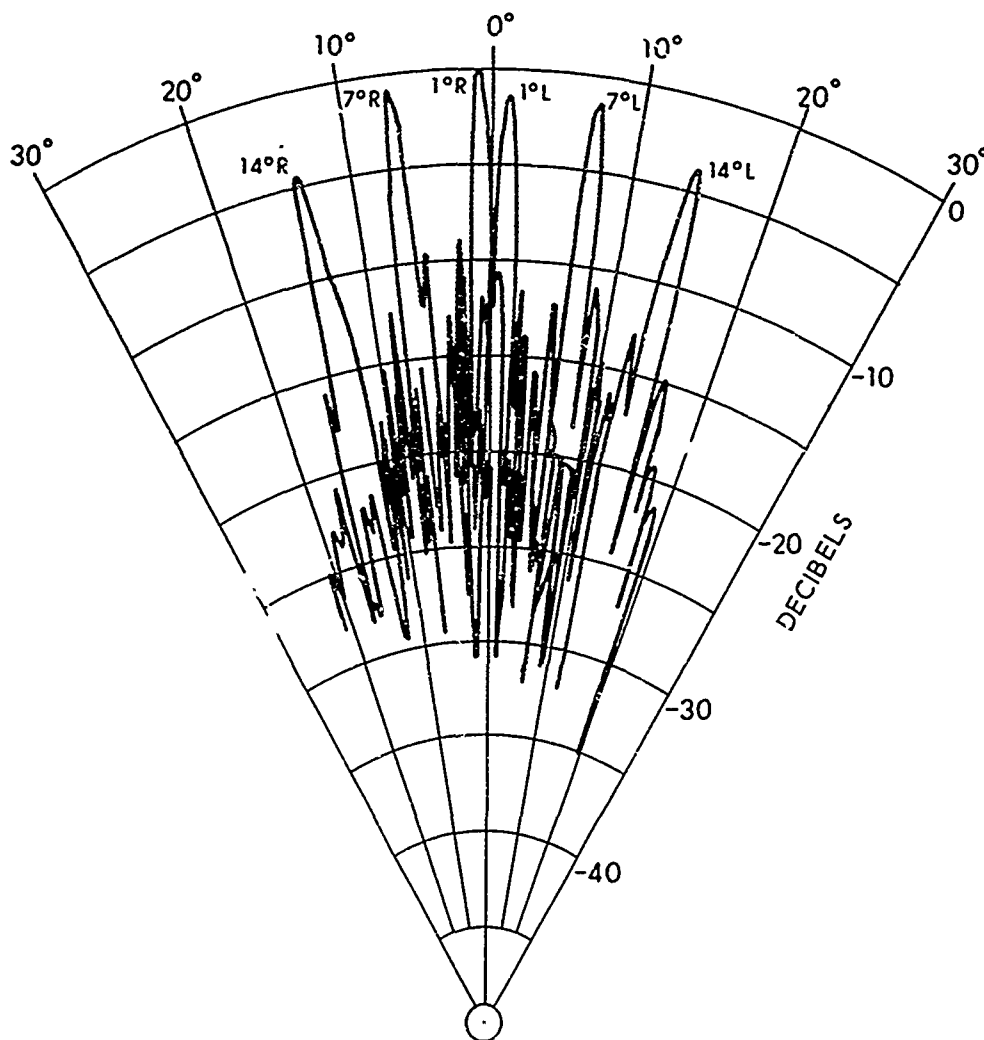
FIGURE 3
POLAR PLOT OF PRIMARY BEAMS
70.00 kHz
0 dB CORRESPONDS TO A SOURCE
LEVEL OF +220 dB re 1 μPa at 1 m

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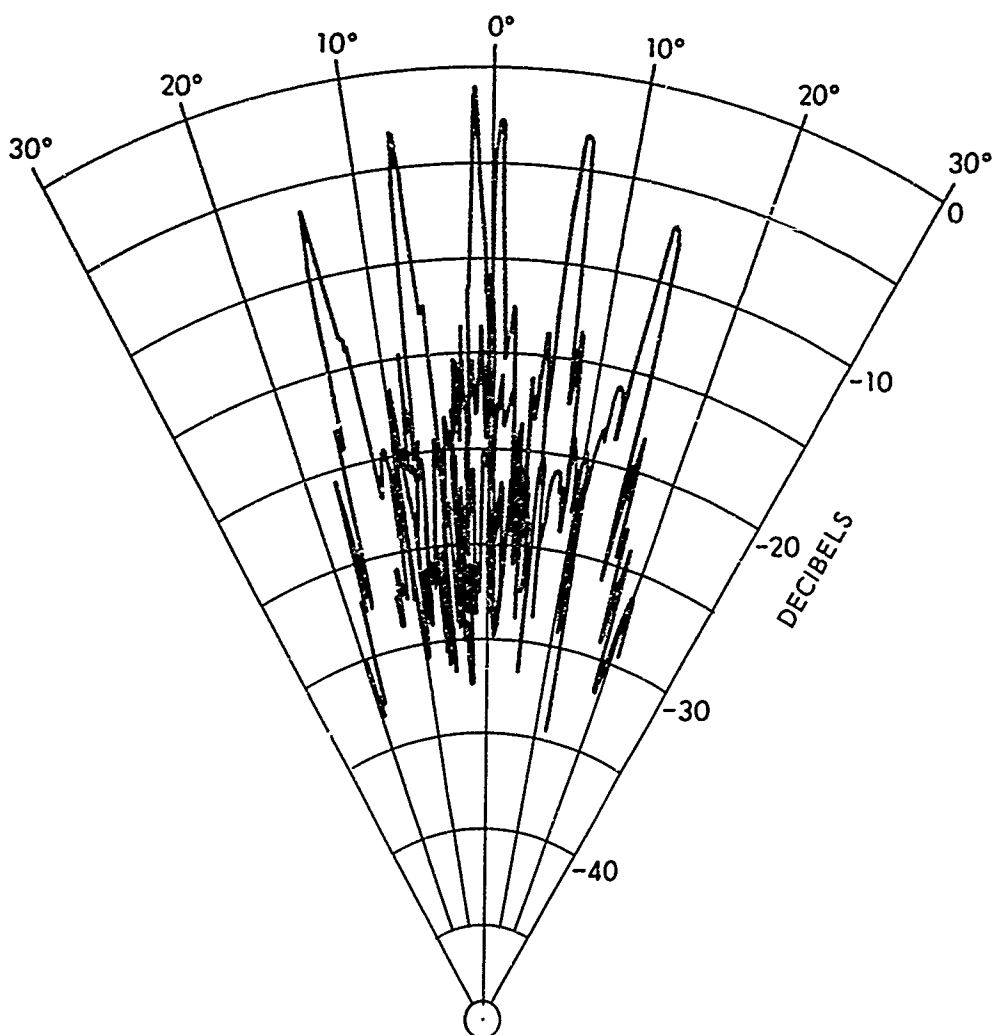FIGURE 4
POLAR PLOT OF PRIMARY BEAMS
83.95 kHz
0 dB CORRESPONDS TO A SOURCE
LEVEL OF +220 dB re 1 μPa at 1 m

10
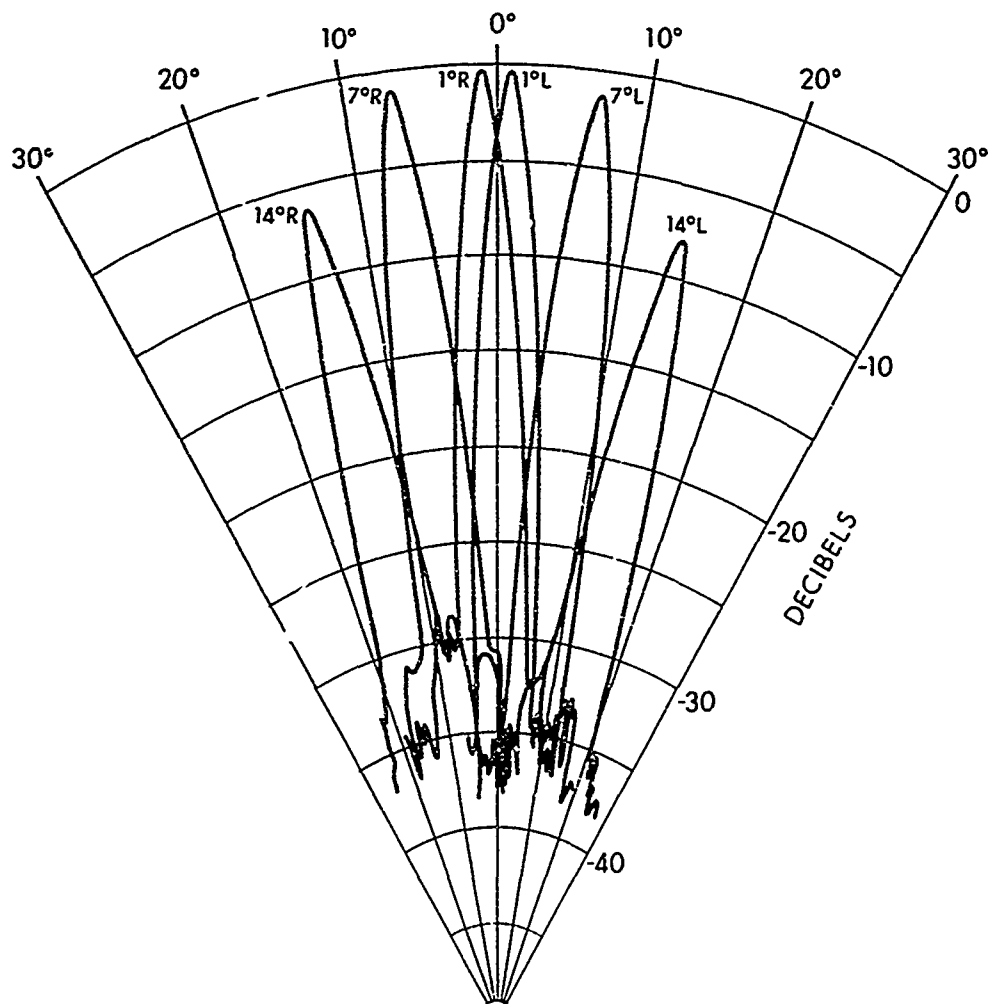
FIGURE 5
POLAR PLOT OF DIFFERENCE FREQUENCY BEAMS
13.95 kHz
0 dB CORRESPONDS TO A SOURCE
LEVEL OF +181 dB re 1 μPa at 1 m

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beam which was deflected 1° from the projector axis was 1.7° wide at its -3 dB points, whereas the beam at 14° deflection was 2.0° wide.

Comparisons of the source levels of the primary beams and the parametric beams are also significant. These data were calculated from pressure measurements at a point on the projector axis, in the farfield of the projector. The source levels thus calculated were +219 and +220 dB re 1 μPa at 1 m for 83.95 and 70 kHz, respectively. The source level of the parametric beam was +181 dB re 1 μPa at 1 m.

III. CODE WORD GENERATION

The system just described was built to transmit FSK code words with
a parametric array in order to observe the transmission and reception of
these code words experimentally and to gain engineering experience in
the construction of such a transmitter.

As stated previously, a code word is a time sequence of acoustical
pulses in which each pulse can have one of several carrier frequencies.
Upon reception, the code word is decoded and used to identify the azimuth
sector into which it was transmitted. Figure 6 illustrates a code word
at the output of the sector selector. This word is composed of the sum
of the two carrier frequency signals and is amplitude modulated to reduce
the frequency side lobes associated with the individual pulses. Starting
from the left hand side of the oscillogram, the two frequencies are 84
and 76 kHz, followed by 84 and 74 kHz, then 84 and 72 kHz, and finally
84 and 70 kHz. As this signal is mixed in the water, it will form an
amplitude modulated time sequence with frequencies of 8, 10, 12, and
14 kHz. Figure 7 illustrates this difference frequency code word measured
in the farfield of the projector. By comparing the envelope functions
shown in Figs. 6 and 7, a difference between the functions in the regions
between the pulses can be seen. The primary frequency waveform approaches
zero in an almost linear fashion, although it does not quite reach zero.
After transmission, however, the difference frequency waveform approaches
zero in an exponential fashion and the function does approach zero between
the pulses. This distortion must be taken into account when generating
the replica waveforms for the correlator and will be discussed further in
the section on the receiver.

There is one final comment which should be made about Fig. 6. The
fine grain structure of the waveform shows the results of combining the two
primary frequencies. One of these primary frequencies was the same in each

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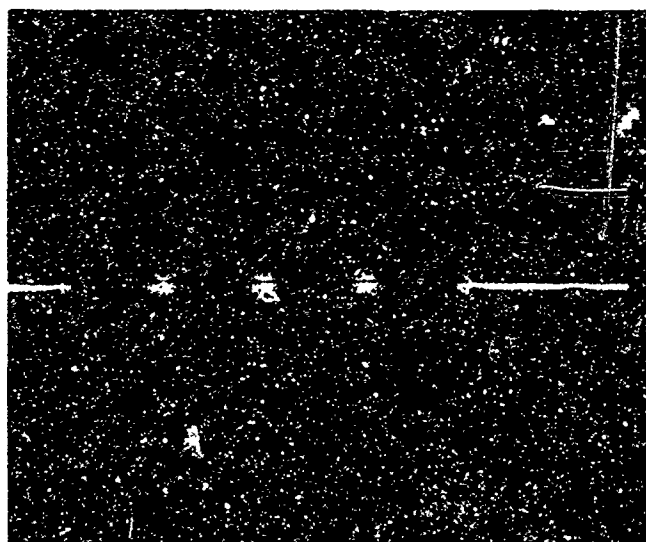
FIGURE 6
OSCILLOGRAM OF THE VOLTAGE WAVEFORM
AT THE OUTPUT OF THE SECTOR SELECTOR
HORIZONTAL SCALE: 2 msec/div
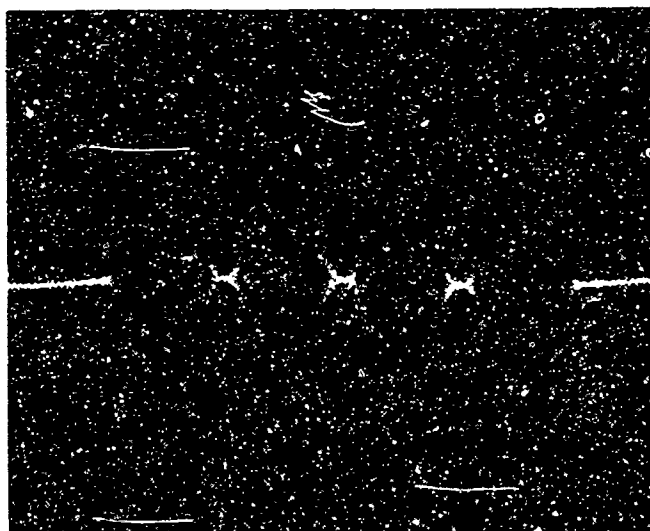
FIGURE 7
DIFFERENCE FREQUENCY PRESSURE WAVEFORM
HORIZONTAL SCALE: 2 msec/div

pulse, while the other was selectable depending upon which difference frequency was desired. The selection of the variable primary frequency was performed by programming the code selector panel. The two primary frequencies were linearly summed before being transmitted by the power amplifier and the projector element.

IV. RECEIVER CHARACTERISTICS

The distinct frequency sequence of the code word gives the code word a unique character which identifies it as the signal transmitted into a particular azimuth segment. The identification of the code word is performed in a broadbeam receiver, which receives signals from all directions of interest simultaneously. The receiver then sorts the signals from the different directions by correlating echoes with appropriate replicas of the transmitted code words. One possible configuration of this receiver would be a hydrophone followed by appropriate amplifiers, which are followed by a parallel set of replica correlators identifying the code words. Each correlator identifies one code word. The block diagram of this receiver (Fig. 8) was the model used for study, although it does not resemble the simple receiver used to collect data. The receiver model will be described in the next few paragraphs.

The hydrophone of the model receiver shown in Fig. 8 has a broad horizontal beam and a narrow vertical beam. The broad horizontal beam allows the continuous reception of echo returns from all directions of interest, while the narrow vertical beam enhances the signal-to-noise ratio.

The hydrophone is followed by a linear low pass filter which is used to attenuate the primary frequency signals. The filter must be very linear (probably passive) in order to prevent difference frequencies from being generated. The frequency response of the filter should be flat up to the highest difference frequency of interest; it should then have a sharp roll off to attenuate the primary frequencies so that they do not generate difference frequencies in the following preamplifier stages.

The low pass filter passes the signal to a low noise, wide dynamic range preamplifier with high fixed gain and with bandwidth appropriate to
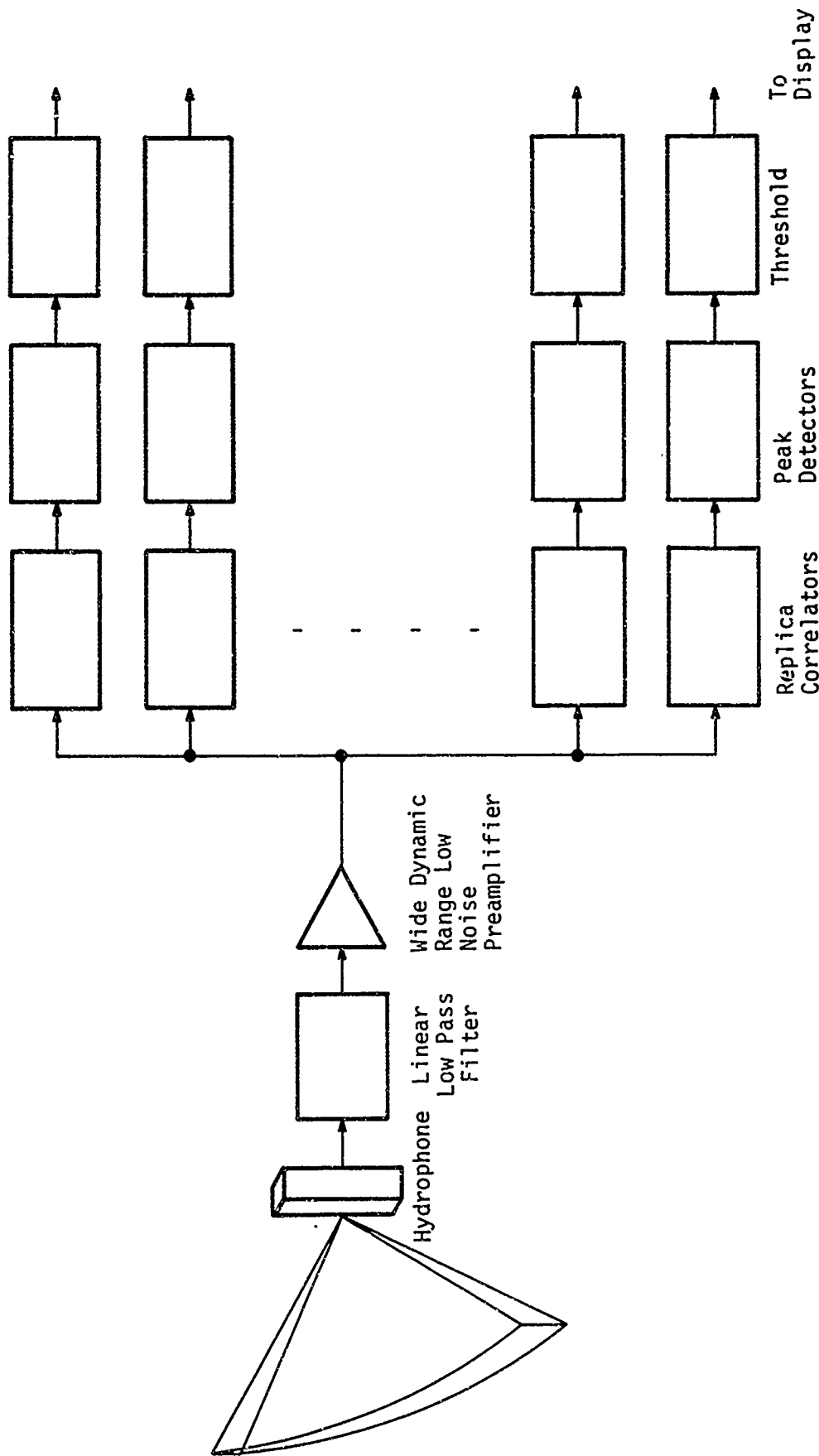
FIGURE 8

BLOCK DIAGRAM OF RECEIVER MODEL

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the signal bandwidth. The fixed gain, wide dynamic range requirement
results from the fact that the receiver will probably be operating con-
tinuously and receiving signals from all ranges simultaneously. If all
of the code words could be transmitted simultaneously, the wide dynamic
range requirement could be relaxed and the preamplifier could employ TVG.

The preamplifier of the model is followed by a set of replica
correlators all connected in parallel, one for each word. These correla-
tors would perform real-time correlations of the returning signal and
separate out the code words matched to their particular replica.

Each correlator is followed by a peak detector and a threshold which
makes the detection decision. The output of each threshold circuit goes
to a particular azimuth sector on a display.

Data were collected to evaluate this model during tests conducted
at LNTS. The next section discusses these tests in detail.

V. EXPERIMENTAL RESULTS

The transmitter and receiver described in sections II and IV were designed for three purposes: (1) to electronically steer a parametric beam, (2) to demonstrate the reflection of a pulsed code word from a target, and (3) to collect data for computer analysis of various receiver schemes. The first purpose was accomplished and reported previously; the other two were to be accomplished in the single experiment described below.

Two objectives of the experiment which will be discussed are (1) to reflect a code word from a target and study the changes to the waveform by the parametric transmitter and by the target; and (2) to reflect code words from a target and record the returns on magnetic tape for the analysis of receiver models. Some of the expected results were not obtained because the transmitter did not produce sufficient source level for the returns to be detected.

In an alteration of the experiment, the target was replaced by a tape loop transponder which recorded and retransmitted the difference frequency signal at a much higher level than that of a target. Although this change to the experiment provided the high signal-to-noise ratio required, it also eliminated any change to the echo structure[3] which would normally be caused by a large target. The transponder, on the other hand, introduced its own distortion to the waveform resulting from electronic distortion and the projector voltage sensitivity. Corrections for these distortions were placed in the computer analysis program.

The tests were conducted at LTTS, with all of the equipment installed on a barge which is permanently moored off-shore (see Fig. 9). Most of the electronic equipment was located in a building at one end of the barge, while the transmitter and receiver were mounted on a vertical column which was affixed to the end of the barge just outside the building. The column
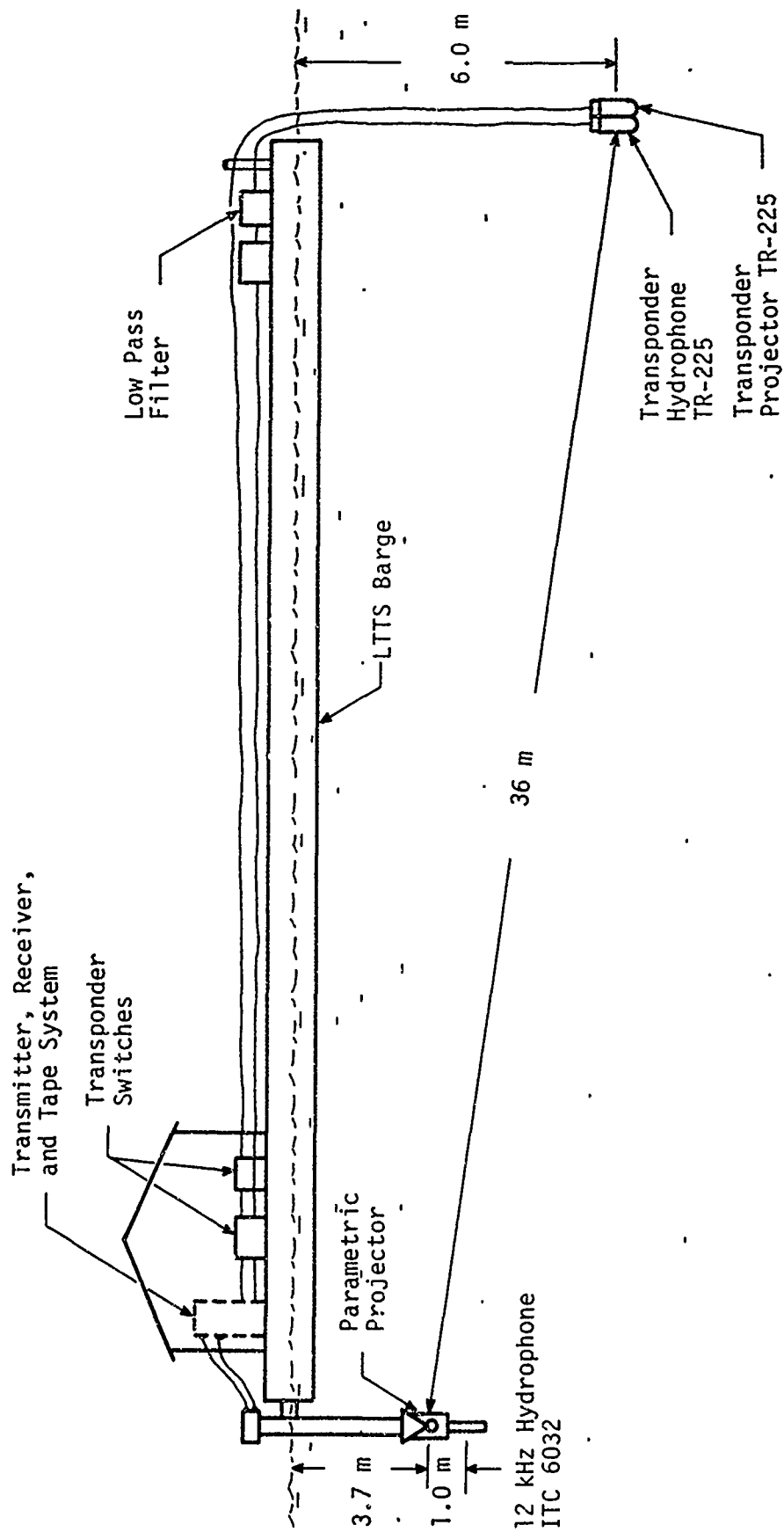
FIGURE 9

ILLUSTRATION OF THE PHYSICAL
LAYOUT OF THE TRANSPONDER EXPERIMENT

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rotated in the horizontal plane and a tilt head provided rotation in the vertical plane perpendicular to the face of the array. The receiver hydrophone was mounted to the transmitter array so that they rotated as one unit.

The two transponder transducers were suspended in the water by their cables from a point at the end of the barge opposite the transmitter and receiver transducers. The distance between the transponder and sonar transducers was 36 m.

The equipment inside the building consisted of the electronic components of the transmitter, the transponder, the receiver, and the recorder. The transmitter, described in section II (see Fig. 2), generated the code word waveforms which were transmitted into the water.

The signal traveled through the water and was received by transponder hydrophone TR-225. (The transponder system is illustrated in Fig. 10.) The primary frequencies were filtered out by a low pass filter and the difference frequency was then amplified and recorded on a 1/4 in. tape recorder. Since the recorder was set to monitor tape, the recorded signal was played back after the time delay required for the tape to pass between the record and the playback heads. After the signal was played back, it was amplified by two power amplifiers and then retransmitted into the water as a difference frequency "reflection."

The receiver used to collect the data was similar to the hypothetical model receiver described in section IV up to the point where the data were placed on magnetic tape. The block diagram for the receiver system is shown in Fig. 11 and can be compared with Fig. 8.

The hydrophone was an ITC 6032 which was mounted to provide a wide horizontal beam (78°) and a narrow vertical beam (16°). The bandwidth was 2 kHz and the center frequency was 10 kHz.
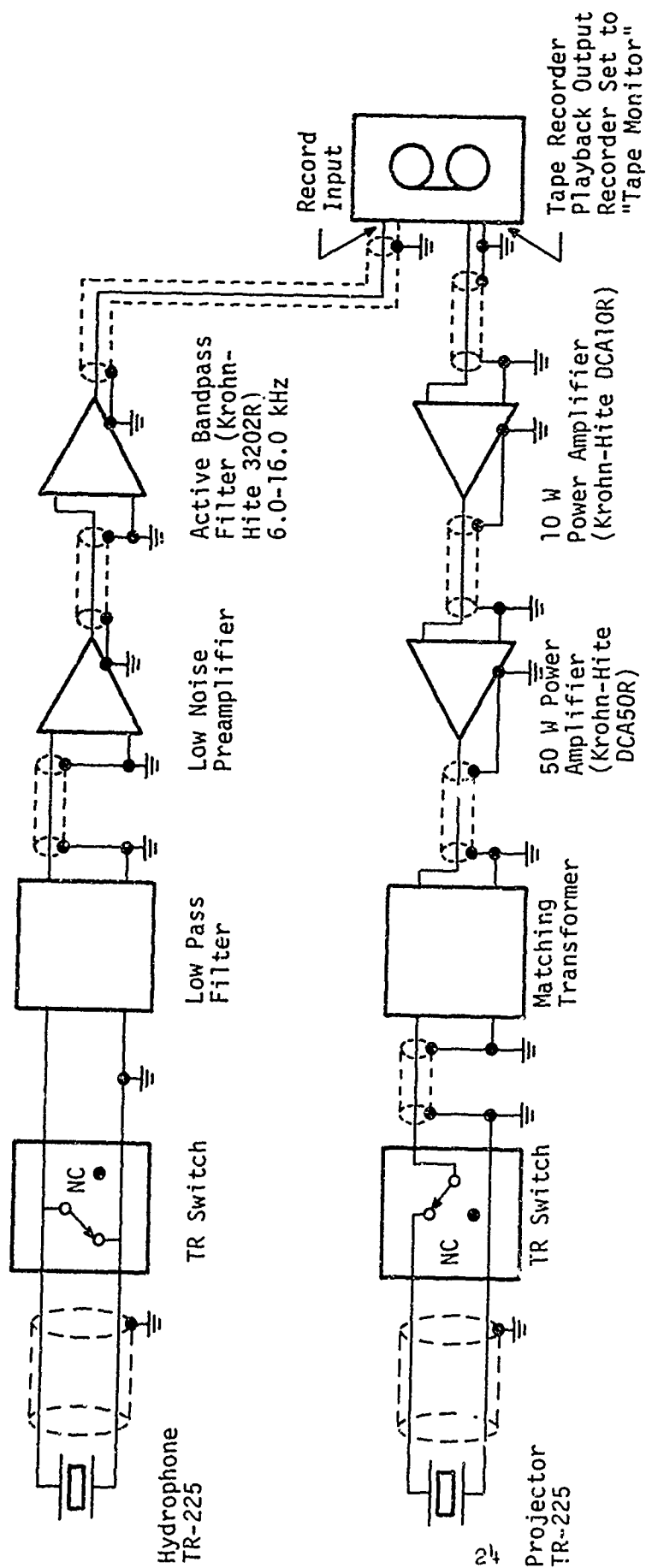
FIGURE 10

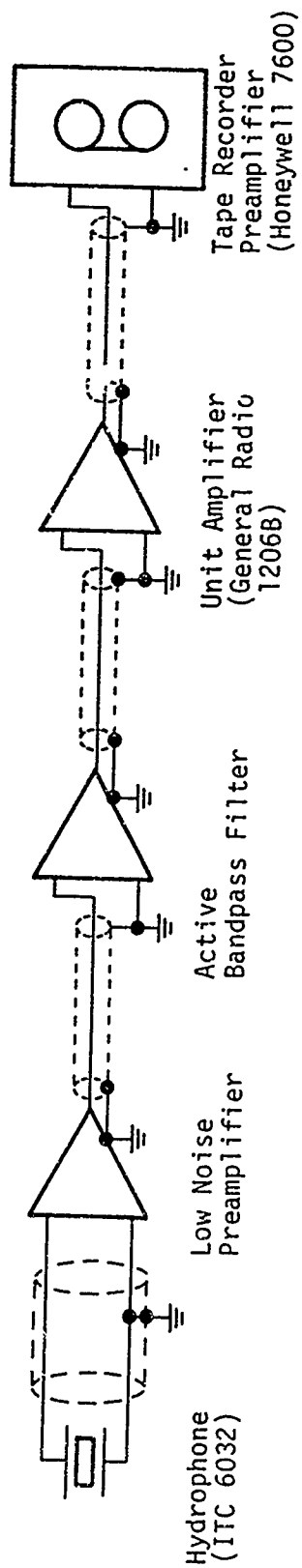BLOCK DIAGRAM OF THE TRANSPONDER SYSTEM

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FIGURE 11

BLOCK DIAGRAM OF RECEIVER
SYSTEM USED FOR TAKING DATA

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The hydrophone output was amplified by a low noise preamplifier with wide bandwidth and high input impedance. The amplified signal was then filtered to limit the bandwidth of the system to reduce noise. The bandpass filter output was transmitted to a unit amplifier which produced the large voltage swings required by the tape recorder.

The tape loop transponder had serious drawbacks which were mentioned only briefly earlier. It not only eliminated the changes in waveform caused by a real target, but it also introduced its own system distortion. The distortion by the transponder was caused by electronic components of the system and by the +12 dB/octave slope of the TR 225 transmit voltage sensitivity. The sum of all of these distortions can be seen by comparing the photographs in Figs. 12, 13, and 14. Figure 12 shows the difference frequency waveform after it is received by the transponder just prior to being recorded. Figure 13 shows the voltage waveform on the TR 225 after playback, and Fig. 14 shows the waveform of the signal just prior to being recorded on data tape. Although the distortion caused by the water and the receiver system are also shown in the waveform of Fig. 14, a large part of the distortior is caused by the transponder. The net distortion of the recorded signal was compensated for in the computer program used to analyze the data.

The tape recorder was a Honeywell 7600, which is a 1/2 in., 7-track instrumentation recorder.

The experimental procedures were performed in two general parts, equipment set-up and data collection. The equipment set-up consisted of assembling all the components of the test system, measuring and adjusting the projector stave voltage amplitude and phase, and measuring beam patterns to ensure that the system was producing a parametric beam. When the beam pattern measurements were completed, the projector was rotated so that the transponder was centered on the 1° left beam (the only beam used in the test). A set of 27 code words, selected so as not to have a crosscorrelation greater than two, was transmitted and recorded. This set is listed in Table I.
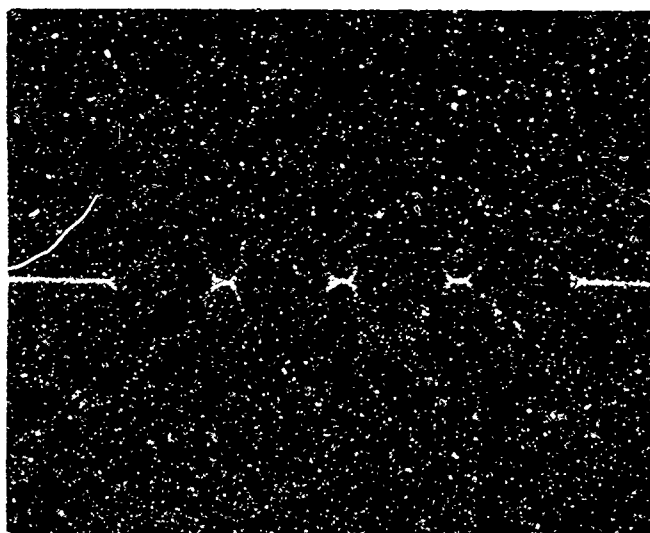
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FIGURE 12
DIFFERENCE FREQUENCY PRESSURE WAVEFORM
AT THE TRANSPONDER HYDROPHONE

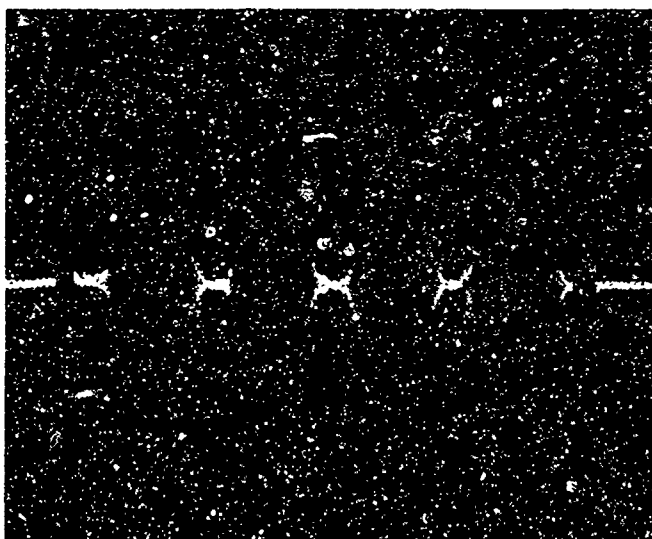FREQUENCIES, LEFT TO RIGHT: 8.86 kHz, 10.58 kHz, 12.30 kHz, 14.0 kHz

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FIGURE 13
VOLTAGE WAVEFORM AT THE TRANSPONDER PROJECTOR

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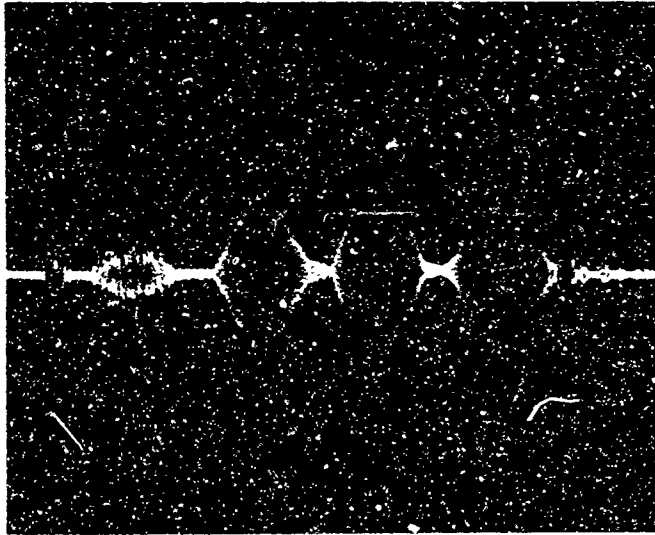
FIGURE 14
VOLTAGE WAVEFORM AT THE INPUT TO
THE INSTRUMENTATION PREAMPLIFIERS

TABLE I

LIST OF CODE WORDS

1112	2243
1131	2322
1143	2341
1211	2411
1222	2423
1233	3311
1244	3334
1321	3421
1332	3432
1412	3443
1424	4312
1441	4422
2134	
2212	
2231	

Computer processing of the data consisted of digitizing the data and placing it on tape, writing a computer program to process the data, and interpreting the results. The data were digitized by normal methods. The word length of the data was 12 bits and the sampling rate was 53 kHz. Thirty samples of each code word were digitized, in addition to an ample segment of lake noise. The purpose of this noise will become apparent in the discussion of the computer program which follows.

The computer program used to process the data is designed to generate the waveform at its output which would be produced by a single replica correlator of the model receiver shown in Fig. 8. The functional block diagram of the computer program is shown in Fig. 15. The primary functions of the program are to read signal and noise and to frequency compensate both, and then determine the mean squared value of signal and noise and adjust the noise for the proper signal-to-noise ratio. The program then adds the signal and the noise and correlates this signal with a stored replica. The correlation result is then normalized to a fixed amplitude and plotted.

The correlation program was used to perform correlations on three code words to verify the operation of the program and to determine how the correlator operated with data. The autocorrelation function of replica (1, 4, 2, 4) was plotted to give a baseline plot and then data words (1, 4, 2, 4), (2, 1, 3, 4), and (2, 2, 3, 1) were correlated to replica (1, 4, 2, 4). In this notation, 1 corresponds to a frequency of 8.86 kHz, 2 to 10.58 kHz, 3 to 12.30 kHz, and 4 to 14.00 kHz.

Plots of the correlations are shown in Figs. 16 through 19. The plots do not all have the same scale because the plotter routine normalized the maximum value in the plot to a fixed height. In Fig. 16 the maximum value was plotted to 1 in. and in Figs. 17 through 19 it was plotted to 2 in. The analysis was done with two signal-to-noise ratios, but the resulting plots were alike.
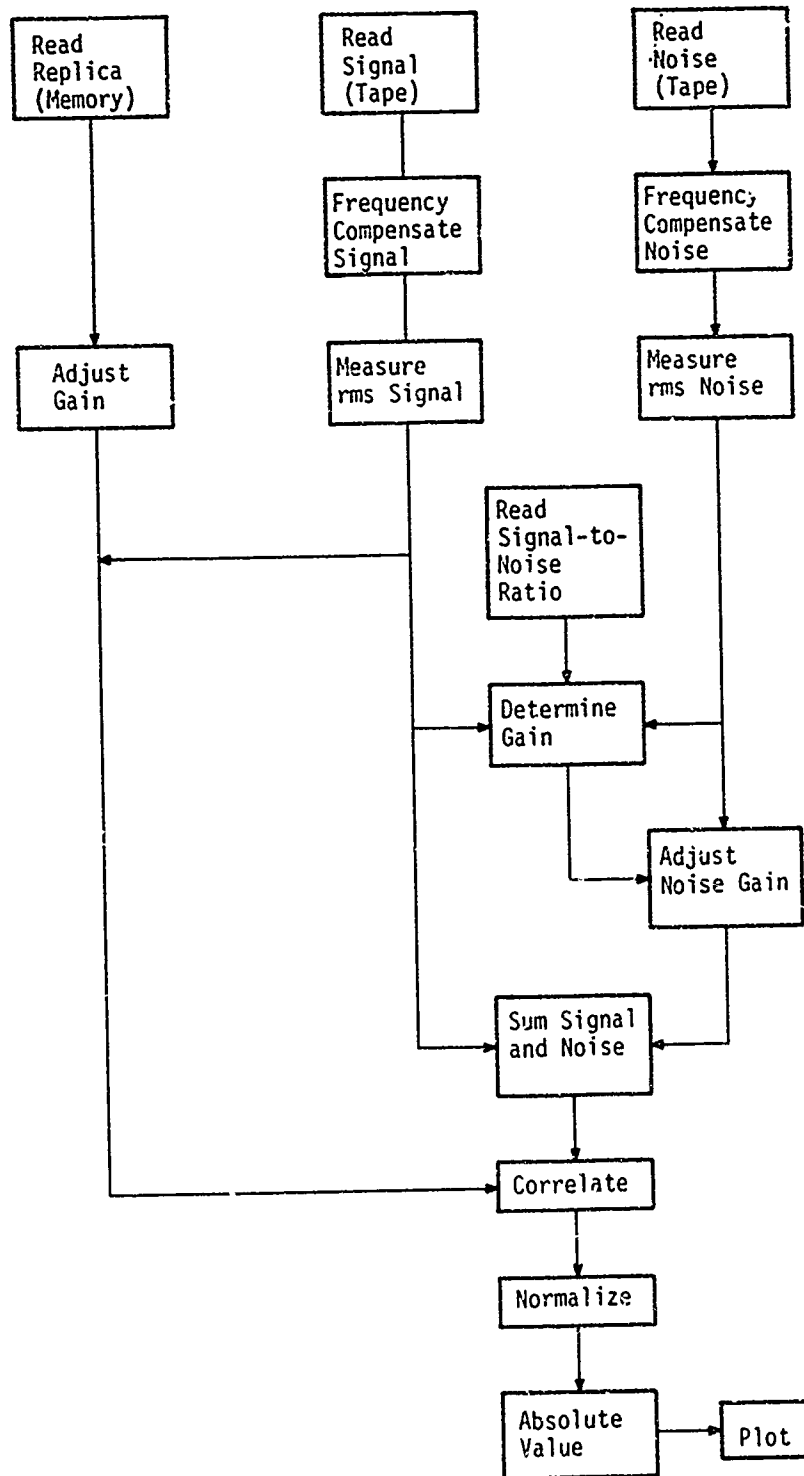
FIGURE 15

BLOCK DIAGRAM OF CORRELATION PROGRAM

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FIGURE 16

THE AUTOCORRELATION FUNCTION OF REPLICA (1, 4, 2, 4)
NORMALIZED TO PLOT A MAXIMUM AMPLITUDE OF 1.0 in.

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FIGURE 17

THE CROSSCORRELATION FUNCTION OF DATA WORD (1, 4, 2, 4)
AND REPLICA (1, 4, 2, 4) NORMALIZED TO PLOT A
MAXIMUM AMPLITUDE OF 2.0 in.

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Correlation Function

$R(\tau) = 1.0$

$R(\tau) = 0.5$

τ – msec

FIGURE 18
THE CROSSCORRELATION FUNCTION OF DATA WORD (2, 1, 3, 4)
AND REPLICA (1, 4, 2, 4) NORMALIZED TO PLOT A
MAXIMUM AMPLITUDE OF 2.0 in.

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Correlation Function
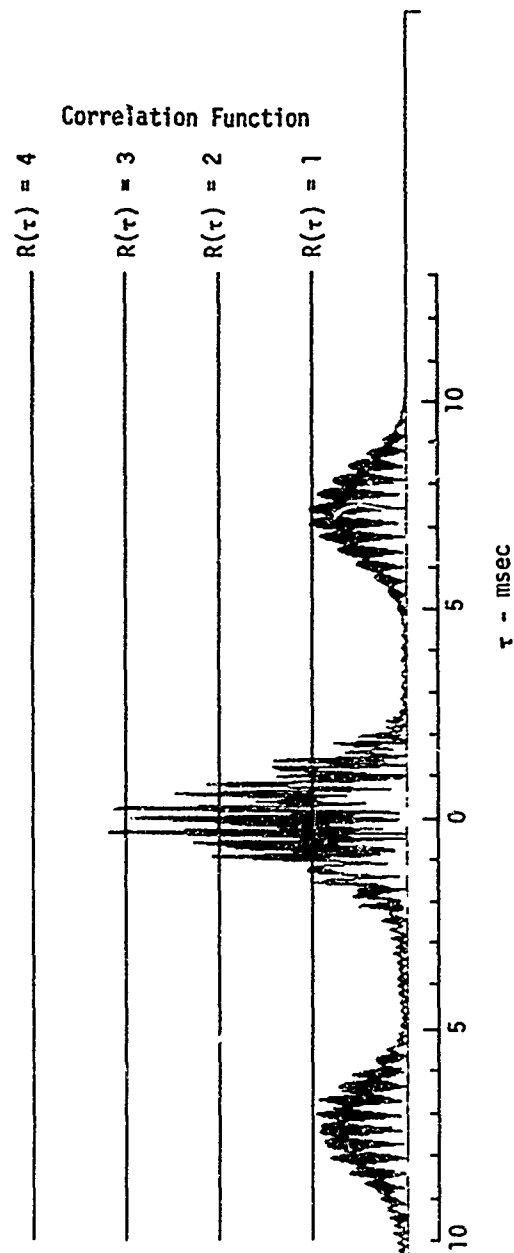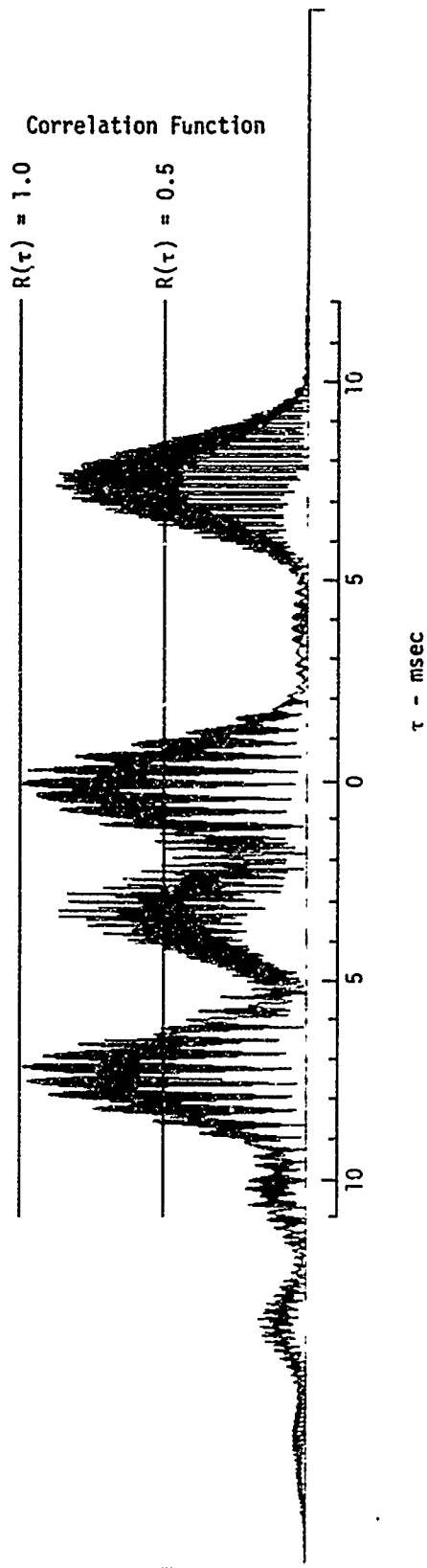
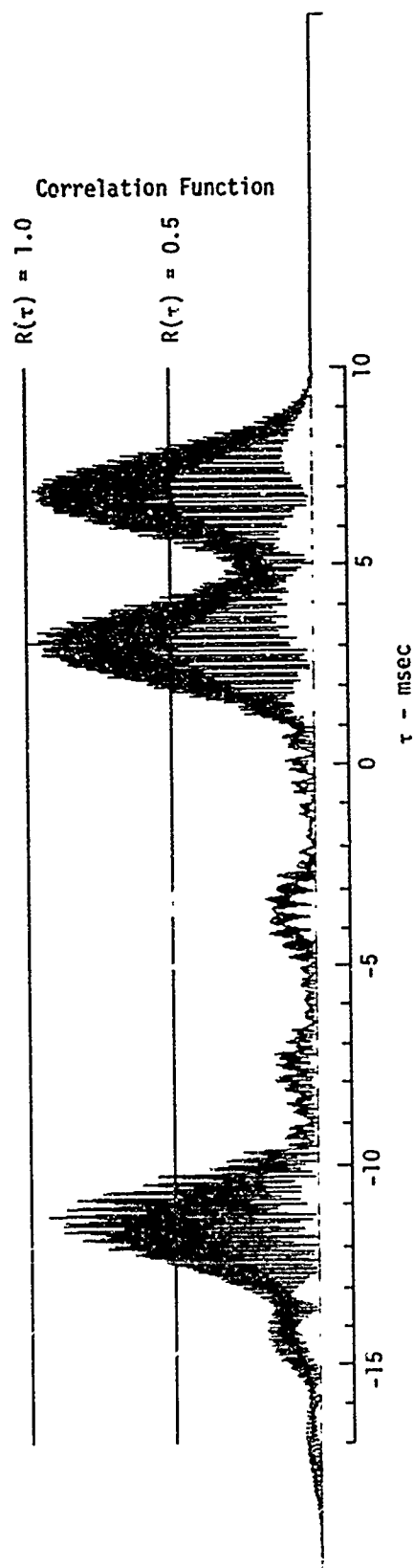$R(\tau) = 1.0$

$R(\tau) = 0.5$

τ – msec

FIGURE 19

THE CROSSCORRELATION FUNCTION OF DATA WORD (2, 2, 3, 1)
AND REPLICA (1, 4, 2, 4) NORMALIZED TO PLOT A
MAXIMUM AMPLITUDE OF 2.0 in.

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RLW 0166-20

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Comparison of the plots reveals some interesting facts. Looking at Figs. 16 and 17, the difference between the autocorrelation of the code word (1, 4, 2, 4), and its counterpart, which is the correlation of data word (1, 4, 2, 4) with replica (1, 4, 2, 4), can be seen. The two functions are very similar in shape, but the center peak which corresponds to the point (τ=0) is down to 3 relative to the side lobe height of 1. Also, two of the peaks adjacent to the center peak are up to about 3.2. The reduced height of the center peak of the data correlation is attributed to distortion and noise, since the autocorrelation plot in Fig. 16 has a peak value of 4 at τ=0.

Again observing Fig. 16, the fine grain structure of the autocorrelation function should be noted. This structure results from the fact that each pulse does not necessarily have the same carrier frequency. The correlation function produces components which are periodic at the difference frequencies of the carrier frequencies contained in the code word. (These difference frequencies should not be confused with the difference frequencies produced by the parametric array, which are now the carrier frequencies.) The difference frequency components in this discussion sum together to produce the fine grain structure seen in the correlation functions. This graininess is a part of the correlation function envelope and is responsible for the increase in bandwidth of a code word with several carrier frequencies over the bandwidth of a code word having only one frequency.

One final comment should be made about the side lobes of the autocorrelation function and all the lobes of the crosscorrelation functions. (See Figs. 17 through 19.) The height of these lobes must be below the detection threshold of the receiver if range resolution is to be preserved and if the number of ambiguities in the azimuth sectors is to remain small. The side lobe height has an impact on the dynamic range of the system, which is now limited to the range of values between the peak of the autocorrelation function and the highest peak

value of any autocorrelation side lobe or crosscorrelation lobe. This restriction is somewhat similar to the dynamic range limitation in conventional linear sonars due to radiation side lobes in the beam patterns. One way to increase the dynamic range of the parametric system would be to use a large number of pulses and a large number of carrier frequencies in each code word, although this approach has practical limitations.

VI. SUMMARY AND CONCLUSIONS

This study has shown that parametrically generated difference
frequency beams can be FSK coded to provide distinct code words for broad
sector coverage parametric sonars. The technique of discriminating the
code words using replica correlation has been demonstrated. Since no
realistic target echoes were used in the evaluation of the beamforming
technique, no conclusions concerning the effectiveness of the system with
echoes modified by target characteristics can be drawn. In addition, the
system was not operated in the presence of reverberation or high ambient
noise to measure the effects of these on the performance.

A continuing program to include the generation of larger code words
and the operation of the system in realistic target/reverberation/noise
environments is recommended.

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